Haptic Pattern Exploration in an Arm-Mounted Solenoid Array

Dean Dijour(✉), Aadya Krishnaprasad, Ian Shei, and Eric Wong

Carnegie Mellon University, Pittsburgh, PA 15213, USA
dijour@cmu.edu

Abstract. A haptic device with a row of 4 solenoids was used to present 7 kinds of pattern stimuli to the forearm. Patterns were uniquely named (e.g. “choppy-motor”), with 3 variants per pattern, designed to be “bad”, “moderate”, and “good” representations of the verbally-announced sensation. Participants were asked to rank each pattern on a 5-point Likert scale, ranking how well a sensation corresponded to its name. Each participant completed two trials, separated by a 5-min break, ranking the 21 randomized pattern variants twice. The results show general likability for most of the “good” variants of the patterns. Pattern likability increased between trials, indicating that increased exposure to this modality may increase believability of patterns. Data shows a positive, near linear relationship between pattern variant quality and participant’s rankings, indicating that participants can distinguish accurate patterns from inaccurate ones.

Keywords: Haptic actuation · Feel effect · Haptic feedback · Haptics media · Human factors · Solenoid actuation · Human-centered computing · Human computer interaction (HCI) · HCI design and evaluation methods · User studies

1 Introduction

With the rise of smartphones and smartwatches, vibrotactile feedback has become the de-facto haptic modality for silently transmitting information to wearers. While this technology is able to effectively convey numeric information and summon a wearer’s attention, it lacks an emotional vocabulary and the rich expressiveness of pressure-based human touch. We wanted to investigate whether pressure stimulation can be an effective and more expressive alternative to vibrotactile stimulation.

Prior research has already been conducted on developing a haptic pattern vocabulary for wearable devices, but this vocabulary has not yet been expanded to technologies that apply direct pressure to the skin, such as a solenoid actuator. We apply this prior haptic vocabulary research as a launchpad to explore the effectiveness and believability of haptic patterns in a 1 × 4 solenoid array. Solenoids employ electromagnetics to create a uniform magnetic field around a wound coil, at the center of which houses a magnet. When the coil is charged, the magnet enables linear motion. Utilizing solenoids as a haptic medium is a novel approach to the process of identifying a haptic vocabulary, as most other studies are vibrotactile in nature. If effective and believable, this technology could serve multiple purposes – transmitting information

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from internet connected devices, providing emotional context to conveyed information, and even enhancing audio-visual sensory experiences.

2 Background and Related Work

Haptic feedback as a means of conveying information is not novel. Extensive research has already been conducted on both actuation mechanisms as well as haptic vocabularies. To find guidelines for haptic patterns, we sought out research from Israr et al. on “feel effects” – vibrotactile haptic patterns which, when coupled with non-haptic events, can enhance an experience [2].

The underlying principle behind this enhancement lies in the integratory effects between vibrotactile and auditory/visual stimuli. Integration effects between these modalities can provide more accurate and faster feedback to the wearers of these kinds of devices [4]. Recent work by the University of British Columbia’s SPIN lab provides an interactive tool for filtering vibrotactile haptic effects based on sensation, emotion, metaphor, and usage facets [3]. This existing body of work created a large set of patterns and .wav files to sample, varying in perceived urgency and perceived pleasantness, which we could attempt to replicate in the pressure modality with a solenoidal device.

In the present research, we describe efforts to convey pattern information on a 1 × 4 solenoid array. Our experiment modulates pattern believability by varying the Stimulus Onset Asynchrony (SOA) between actuators, the On Time of each actuator, and the Off Time of each actuator. With just these three variable parameters, our simple device is capable of producing thousands of unique patterns.

3 Method

3.1 Participants

Five Carnegie Mellon University undergraduate students (N = 5, 2 female, 3 male), ages 19 to 21 (M = 20.4 years, SD = 0.8 years), having no prior experience with pressure-based haptic wearable devices participated in $12/hour paid studies. All gave informed consent under a protocol approved by the Carnegie Mellon Institutional Review Board. All subjects were right- handed, and were asked to use their right arm for the study (Figs. 1, 2).

3.2 Device

We developed a simple Arduino controllable device, consisting of 4 neodymium magnets (0.107″ height, 0.589″ diameter), a fused filament fabrication (FFF) 3D-printed polylactic acid (PLA) base plate (7.25″ length, 1.7″ width, 0.44″ height), enameled copper wire, and FFF 3D-printed PLA spacer discs (same dimensions as magnets), along with solenoid control circuitry. Each cell in the 1 × 4 array of solenoids is individually addressable, and can be actuated at a maximum frequency of once

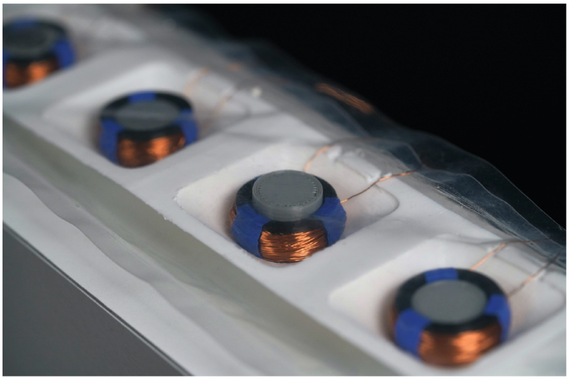

Fig. 1. Each cell wall is wound in enameled copper wire. The cell houses a neodymium magnet, with a spacer on top of it. The protruding piece, 2nd from the right in this picture, shows what an activated cell looks like.

```
void heavyRain(int dwellDuration, int lowRange, int highRange) {
    int target1 = random(3, 7);
  digitalWrite(target1, HIGH);
  delay(dwellDuration);

  int target2 = random(3, 7);
  digitalWrite(target2, HIGH);
  delay(dwellDuration);

  int target3 = random(3,7);
  digitalWrite(target3, HIGH);
  delay(dwellDuration);

  int target4 = random(3,7);
  digitalWrite(target4, HIGH);
  delay(dwellDuration);

  turnOff(target1, random(lowRange, highRange));
  turnOff(target2, random(lowRange, highRange));
  turnOff(target3, random(lowRange, highRange));
  turnOff(target4, random(lowRange, highRange));
}

//utility function to turn off a given pin after a set duration
void turnOff(int pin, int duration) {
  delay(duration);
  digitalWrite(pin, LOW);
}
```

Fig. 2. The Arduino code for the "heavy rain" pattern. This function takes three parameters, and generates random patterns.

every 10 ms (100 Hz). At 100 Hz, the magnet is effectively suspended in mid-air, but due to its high power, the device outputs both vibrotactile as well as standard pressure sensations. At lower activation frequencies, the device produces tapping sensations on the surface of the skin. We mounted this solenoid enclosure to a box constructed of foam core, to elevate the surface and align it with the armrest of the participant's chair. This allowed the device to function as a forearm rest for participants, enabling them to lay their arm down flat, directly on top of the actuators.

3.3 Stimuli

We identified 7 distinct patterns, through a combination of informal prior user testing, consulting with Professor Roberta Klatzky, and from the research insights in the VibViz and Feel Effects studies [Klatzky, personal communication] [2, 3]. Patterns like "light rain" and "racing heart beat" were chosen due to the likelihood that participants had felt the real sensations before, and would be able to give ecologically valid ratings. Other patterns were chosen to see if more unusual and interesting sensations could be simulated.

We initially created "good" variants of each pattern, using samples from the aforementioned research, and mimicking cadences of reference sensations, such as those created by heartbeats and motors. We modulated the three parameters (SOA, On Time, Off Time) until we were content that the quality of the patterns reflected the word descriptors. Creating "moderate" and "bad" variants involved modulating the parameters from the "good" variants in ways that made them progressively more dissimilar to the initial pattern we created (Figs. 3, 4) (Table 1).

Fig. 3. Participants (one of the researchers, in this picture) were instructed to sit upright and comfortable in a chair, while resting their forearm on the device. Participants were first given a test pattern to ensure they were correctly positioned to feel all 4 actuators.

Fig. 4. Close up of participant resting their arm on the device.

Table 1. Each of the 7 patterns, along with the parameters modulated for each of the three variants, can be seen in the table above. All parameters are in milliseconds. The first, second, and third numbers in parentheses next to each parameter correspond to the "bad," "moderate," and "good" variants of each pattern.

Pattern	Description	Parameters (ms)
Frog jumping	All cells turn on sequentially	On Time (500, 700, 100), Off Time (500, 100, 500)
Light rain	Random short sequential pulses in random locations	On Time (20, 240, 140)
Heavy rain	Random short simultaneous pulses in random locations, with random delay	On Time (15, 100, 50), decay Low (100, 50, 10), decay High (150, 100, 50)
Calm heart beat	One cell turns on and off, repeatedly	On Time (200, 500, 500), Off Time (300, 500, 900)
Racing heart beat	One cell turns on and off, quickly, repeatedly	On Time (100, 125, 167), Off Time (180, 225, 300)
Smooth motor	All calls turn on and off *very* quickly, repeatedly	On Time (25, 20, 10) – off time is same
Choppy motor	All cells turn on and off quickly, repeatedly	On Time (200, 100, 50) – off time is same

3.4 Ranking Task

Participants were briefed on the experiment, how to use the Likert scale, and were encouraged to use the full range of the scale. The scale ranged from "Unacceptable," "Acceptable," "Good," "Very Good," to "That's it!". "Unacceptable" implies the pattern feels nothing like its name, and "That's it!" implies a perfect real-world match. This scale was adapted from the work of Israr et al., since the task of ranking believability was quite similar to portions of their study [2]. Each participant was fitted with both ear plugs and noise-cancelling headphones, to ensure they could not hear the device. They were also instructed not to look at the device while the trials were in progress. Participants were first shown a sample pattern, entitled "Wave," before they began the experiment.

When they were seated comfortably and could feel all four actuators, the first half of the experiment began. Each of the 7 pattern groups, split by their 3 variants, was presented in a randomized order, for a total of 21 rankings. Before each pattern was initialized, participants were verbally told the name of the pattern they were going to rate. Participants had up to 30 s to feel the pattern and rate it, but in practice, most only took 5–10 s to provide a rating. At the end of the first half of the experiment, participants were given a five-minute break. After the break was over, Trial 2 began, and participants were asked to rank the same 21 pattern variants they had felt in the Trial 1, in a re-randomized order. The participants were not told that both trials used the same pattern set, but it is possible that they concluded this fact by the end of the second trial.

4 Results

4.1 Variant Preference and Pattern Believability

Across both trials, mean pattern scores indicate that participants were generally in agreement with our intended believability of variants. Pattern variants we designed to be “bad” were rated, on average, as less believable than ones designed to be “good”. As can be seen in Fig. 5, every pattern’s mean scores, in both trials, exhibit a positive slope from the “bad” to “good” variants. This confirms that, within the set of our designed patterns, participants were able to sense the authenticity of a pattern, and agreed with our design decisions. It should be noted that this positive slope only explains participants’ relative preference for patterns, within a small set of possible choices – it does not yet explain the quality or utility of the patterns tested.

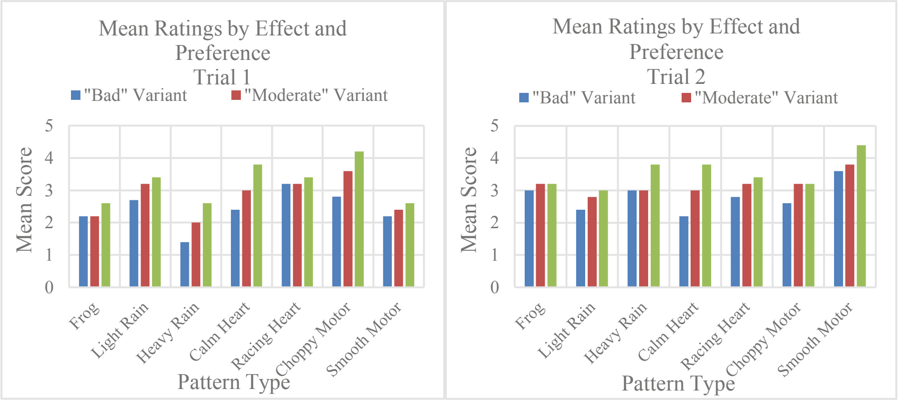

Fig. 5. These charts graph the average scores for 3 variants of the 7 patterns, for both Trials. Trial 1 favorites were the “good” variants of choppy motor, calm heartbeat, and light rain. Trial 2 favorites were the “good” variants of the smooth motor, heavy rain, and calm heartbeat.

In terms of absolute believability, only the “choppy motor” in Trial 1, and the “smooth motor” in Trial 2, achieved average scores above a 4 (meaning “Very good”). These patterns are nearly identical, wherein all 4 cells turn on and off at a regular interval. The “good” variants of these patterns also have activation frequencies nearly 10–50 times greater than those of other patterns. This could indicate a preference for strong (more simultaneously active cells) and frequent (rate of actuation) stimulation. Overall though, the “good” variants of every pattern saw ratings around a 3, which shows that the majority of these patterns are “good” and should be viable for further exploration.

4.2 Inter-trial Sensitivity and Variability

Trial 1's mean rating for all patterns was 2.814, while Trial 2's mean was 3.171 – a 12.689% increase in believability between trials. In Trial 1, participants scored 9/21 (42.86%) of the patterns at an average of 3 or above. This was in line with our expectations, since 7 of the pattern variants were purposely "bad," and another 7 were "moderate". In Trial 2, participants scored 16/21 (76.19%) of the patterns at an average of 3 or above. This is a significant, 77.76% increase in average "good" ratings, despite any change in the pattern stimuli.

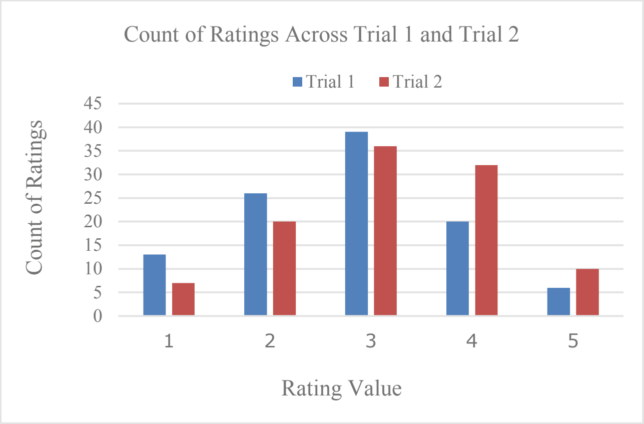

Fig. 6. This chart visualizes the count of individual scores in both trials. Trial 1 appeared more scrutinous, with almost double the "unacceptable" (1) ratings as Trial 2. Trial 2 markedly increased the count of "very good" (4) ratings.

One might wonder if participants were simply more lenient with their ratings, and shifted over their prior scores from Trial 1. As can be seen in Fig. 6, the largest change between trials was in the "very good" category, with Trial 2 increasing by a count of 12.

However, the average 4+ scores for specific variants is identical between trials, and it seems that participants are still hesitant to rate most patterns as "very good" or "that's it!". Both Trial 1 and Trial 2 saw only 1 pattern variant achieve an average score of 4 or above ("choppy motor" and "smooth motor", respectively). Regardless, participants did feel that fewer patterns were "unacceptable" or "acceptable" in Trial 2. Additionally, every participant decreased their usage of the "unacceptable" and "acceptable" ranking, and increased their usage of "good".

5 Discussion

5.1 Data

The significant individual score differences between Trial 1 and Trial 2 are interesting. One could speculate that the duration of exposure to this haptic device may be positively correlated with believability of pattern stimuli. Alternatively, participants may not have initially been sensitized to the stimulus in Trial 1, and as such, stimulus sensitivity may vary as a function of exposure time, rather than believability. Perhaps Trial 1's initial ratings were lower because participants needed device adjustment time, or may not have fully understood the experiment. For this reason, we will not be discussing much data from Trial 1, and we will treat it as an acclimation period.

The positive slope between "bad" and "good" variant ratings seen in Trial 2 is a strong indication that participants, at the very minimum, have the ability to discriminate between authentic and inauthentic pattern stimuli. Further, the average rating for all 21 variants of 3.171 indicates that the pattern stimuli in this study are "good" and believable to a degree – these could benefit from further exploration.

Participants also identified a clear favorite in the smooth motor, which operates at 100 Hz, and feels very similar to vibration emitted by mobile phones and smart watches. It is difficult to determine what makes some patterns more believable than others, since all of our patterns varied widely in cell actuation count and actuation frequency. It would be ideal to do follow-up studies to measure the impact of cell actuation count and actuation frequency, to build a guide for designing the most believable patterns.

5.2 Limitations

As shown in Figs. 7 and 8, the ideal form factor for this technology is a wearable, wrist mounted device. Unlike the prototype used in this study, this device would have 3 × 12 solenoids, allowing for multi-row stimulation. Such a device could encompass the arm and provide human like stimulation. The present prototype contained only 1 row of solenoids, so complex effects like "rain" had to be abstracted into a single row form. Naturally, with multiple rows and far more cells, a device could produce significantly more convincing patterns.

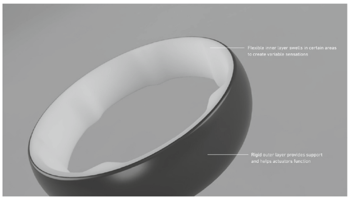

Fig. 7. Idealized form factor as a wrist-mounted wearable. The device would have 360 degrees of actuation, as well as 2 dimensions of actuation (more than just one row, unlike the prototype in this study).

When activated, the solenoids in our prototype were clearly perceptible and distinct, but due to the nature of the mode of actuation, they only had a maximum displacement of half of the solenoid length. Using a more advanced method of linear movement, the ability to push harder and higher would give this device the power to truly grab a user's attention. At present, the device is more subtle, and requires the wearer to focus on feeling the patterns. In order to be useful in the real world, the device must have sufficient power to be effortlessly noticeable.

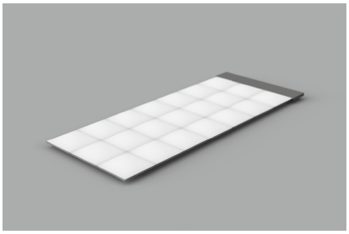

Fig. 8. Unrolled version of the idealized form factor. The device would be made up of 3 × 12 solenoids, enabling the use of a richer haptic vocabulary.

5.3 Further Applications

The study results show that participants can be made to believe they are feeling a sensation that is actually not happening to them. This is not a novel phenomenon, and many haptic technologies can accomplish this with verbal priming. The key distinction for our device will be the ability to "tap," "poke," and "grab".

Vibrotactile actuators cannot authentically simulate these kinds of feelings, and prior research shows that skin becomes overly sensitized to vibrotactile stimulation as time goes on [1]. Vibrotactile stimulation inherently introduces a great deal of noise and interference when multiple actuators are activated simultaneously - creating sensations with more than 2 active actuators becomes noisy and unclear [1]. With pressure-based stimulation, this noise and interference is minimized, and it could be possible to construct wearable devices that evoke clear sensations of grabbing, stroking, poking, etc. – opening a new communication frontier based on rich emotive information. Such a device could calm its wearer down with gentle pulsing, or perhaps, command attention with a strong grab by pulsing a circular array of actuators. The possibilities for this kind of communication are virtually endless, but this study demonstrates the potential for these devices.

6 Conclusion

Although our test device was simple, the implications of our results are clear – pressure-based haptic stimulation has the potential to integrate multi-modal experiences, contextualize information, and create a more emotive future. Further testing, with more subjects, more patterns, and a more powerful device could yield even more insights into the world of haptic language design, and pave a way forward to introduce these insights into the real world.

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